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PROF. HARTT ON THE BRAZILIAN SANDSTONE REEFS.

BY RICHARD RATHBUN.

THE sea-coast of Brazil, from the mouth of the Amazonas to near Victoria, is generally low and of quite uniform character, being everywhere faced with broad, open beaches of sand that extend for miles and miles without interruption. A less inviting region than this to the explorer can scarcely be imagined, and it stands in marked contrast with the more tempting inland districts, especially those in the Amazonian valley, which have always caused Brazil to be considered a sort of naturalists' paradise. It was little suspected, until a few years ago, that this unattractive coast harbored very extensive and curious coral reefs, and displayed, in connection with its beaches, interesting phenomena whose true character had been entirely misunderstood.

Some of the earlier writers on Brazil endeavored to describe this region, relying either on their own imperfect observations, or on what others had seen, and adding, apparently, here and there, numerous details, the products of their own fertile brains, perhaps, to smooth over and complete the sketch.

These very inaccurate accounts gave credence to the existence of a long bar or reef of stone, bordering the entire coast from north of Cape St. Roque to the southward of Bahia. Piso, in his work published in 1648, described this reef, and he has been copied over and over again by nearly every author who has written on this subject since his time, no one ever having taken the trouble to test the accuracy of his statements. Even Staff-Commander Penn, in the "South American Coast Pilot,"

treats of "the *recife*, a singular ridge of coral rock," bordering the coast, at a distance from it of about half a mile to three miles or more, and extending from the north-east part of Brazil to south of Bahia. According to his accounts, the reef is about sixteen feet broad at the top, forming a natural breakwater, with smooth and shallow water inside, affording a channel for coasters. "It is broken occasionally, and forms, by the openings, entrances to the greater part of the ports, rivers and creeks on the coast."

Gardner describes the mythical reef in nearly the same terms, and there can be no doubting the fact that these two writers have reproduced Piso's old description, with many additional details thrown in gratuitously.

It is needless to state that these accounts of a continuous reef were without foundation, but they served, more or less, to mould the world's ideas of the character of that coast up to the time when the late Prof. Ch. Fred. Hartt published the results of his careful and painstaking explorations of that region. Whether this observer was the first to rightly interpret the structure of the Central Brazilian coast or not, he, at least, has given the only extended and intelligible account of it. He has shown that although stone reefs occur at many localities, they are far from being universal, or even continuous over any great distance.

Quite distinct from these are a series of coral reefs, often lying near the shore, but much more developed farther out, rising upward from the surface of the submerged border of the continent.

As a member of the Thayer Expedition in 1865, Prof. Hartt examined two quite perfect stone reefs, at Porto Seguro and Santa Cruz, in the province of Bahia, and at several places in the province of Espirito Santo he also found traces of the same structure, lying near the beach, however, and not forming true reefs. On his second trip, in 1867, he was able to study the larger and more perfect stone reef of Pernambuco, and to detect a similar formation on the beaches about Bahia. A full statement of these investigations, and of his theory of the origin of the reefs, is given in his "Geology and Physical Geography of Brazil," published in 1870. Darwin, who touched at Pernambuco on his memorable voyage, arrived at nearly the same conclusions regarding the mode of formation of the reef at that place, as did Prof. Hartt, but his description of it is very brief.

Immediately upon the organization of the Geological Commission of Brazil, in 1875, under the leadership of Prof. Hartt, active field operations were commenced in the province of Pernambuco, and another opportunity was thus afforded the late chief to examine that most noted of all these natural breakwaters. With the larger force and more perfect appliances now at his command, he proceeded to carefully map out the reef and its surroundings, and to study in detail every feature connected with it. This extended investigation did not materially alter his previously-formed ideas as to the true character and mode of growth of the reef, but there were added many facts not before observed.

Other stone reefs, at Cape Sto-Agostinho, Parahyba do Norte, etc., were explored by the Commission, and the conclusions arrived at, after comparing the results of all these studies, are of great interest and importance, demonstrating that on the coast of Brazil conditions obtain for the united working of a set of simple forces which, apparently, are not perfectly combined, at least with the same results, in any other part of the world. As we can best understand these phenomena after becoming acquainted with the structure and appearance of a single reef, we will first describe the one at Pernambuco, partly in the very words of Prof. Hartt, and then discuss the subject as a whole.

Just to the south of the city of Pernambuco, a little river breaks through the land, and would open directly into the sea were it not that a narrow wall of stone, running in a general way parallel to the shore, carries its course some distance farther north, to beyond the limits of the city. Another small river, near its mouth flowing parallel with the sea, and separated from it by only a narrow strip of land, runs through the city of Pernambuco, and opens also behind the reef.

There is thus formed a small and very shallow bay, which is continued northward past the city, as a rather narrow channel, having a width of only a hundred rods or less, and a depth of but a few fathoms. The outlet to this channel is close to the northern end of the reef, and is so shallow as to admit only coasting steamers and vessels of ordinary draught. It is, however, the protecting reef and not the narrow harbor that interests us now.

Standing upon some prominent point near the shore, in Pernambuco, we can plainly trace this narrow strip of stone from its commencement, about opposite the ancient *fortaleza do Brum*,

situated to the north of the city, to the Ilha dos Pinhos, at the south. Its course is south, a few degrees west, and it runs in a nearly straight and unbroken line to near the latter place, where, however, it is cut through so as to afford a passage-way for small boats and jangadas. From this point to its southern end it is much broken up and generally irregular.

But to examine it the more closely we must land upon it at low tide, and walk along its nearly level surface, stopping at times to investigate any unusual appearance that may attract our attention.

The reef rock is a sandstone, of a light brownish tint when wet by the waves, and is formed of siliceous sand and rounded pebbles, mingled with which are many perfect and broken shells, all firmly cemented together by carbonate of lime. The most abundant shell in the sandstone is a species of *Venus*, still very common on the neighboring shores, and preserving in the rock its natural colors.

At its northern end the reef is very narrow and has, apparently, been much undermined and worn by the waves, for it is lower here than to the south, and the sandstone lies in immense blocks, inclined toward the sea. To increase its height and better protect the harbor at this place, an artificial wall, partly of brick and mortar, partly of reef stone clamped together, has been constructed. That the reef formerly extended much farther northward is evident from the existence of an isolated mass of reef rock just off the northern end, and of a stretch of submerged reef beyond the channel. Upon the extreme point of the reef stands the Pernambuco light-house, and a short distance from it is a little old octagonal fort, called Picao, built of reef stone, and occupying the entire width of the reef.

Following southward, the reef becomes broader and more level on top, but is still very irregular at the sides. In front of the city it has an average width of about two hundred and fifty feet, and a height equal to about that of high tide, though on account of the great commotion made by the waves at such times, it is impossible to exactly determine this fact. As to the thickness of the reef, it must reach down to below the level of low tide, because the rock is never entirely uncovered by the water.

The highest part of the reef forms a broad belt of varying width, whose axis lies a little to the inside of that of the reef.

From this belt the surface slopes more or less strongly on both sides, but presents quite different characters, resulting from differences in exposure. The outer side of the reef has become very irregular from the constant beating of the surf, and is pierced with innumerable cavities of sea-urchins and thickly overgrown with sea-weeds and calcareous incrustations. The inner side, after a more or less rapid landward slope, breaks down abruptly and irregularly, and often presents an overhanging edge.

The reef is cut up into large blocks by joints or cracks, which, though quite variable in their courses, may be reduced to two general series, one parallel to the axis of the reef, the other transverse to it; but many run obliquely or radiate from a common center, as though the reef at that point had settled down upon a hard underlying spot; sometimes they form a tangled maze. These joints are vertical or highly inclined, and the angular masses resulting from them are likely to be detached, on the outer side of the reef by the force of the waves, and on the inner side by the undermining action of the currents in the harbor. In this manner the margins of the reef have been made very jagged, the outer being the most irregular. On the upper surface of the reef, where there has been no dislocation, the joints tend to widen by the action of the surf and by chemical decomposition. There are thus formed open passages, a foot to a yard or more in width, and with a considerable depth of water. In these we always find a rich collection of marine animals, corals and other polyps predominating.

Now let us inspect more minutely the character of the surface, and the many foreign objects living or growing upon it, which tend either to protect it from wear, or to gradually and surely effect its destruction. As stated above, sea-urchins are burrowing into its outer edge. There is only a single species on the Brazilian coast that is able to excavate in the solid rock; it is the *Echinometra subangularis*, everywhere abundant, and possessed of stout, sharply-pointed spines. On abrupt slopes of the reef, this diligent worker forms rounded holes, having only a slight depth, but where the slope is gradual, the holes are much longer, running either directly inwards, or in a more or less winding way, being sometimes curved or bent upon themselves. They have often a length of four or five feet, and a width of three or four inches, the urchin apparently occupying the lower end of the elongate holes.

Whether the process by which the boring is accomplished, in this special case, is chemical or mechanical, it is very certain that this sea-urchin is able to resort to the latter means at times, for its excavations are common in the trap and gneiss rocks of many parts of the coast.

The sea-urchin holes, enlarged by the action of the surf, give rise to cavities and irregular pools on the surface of the reef, and these are deepened and widened by the dissolving action of the water left stagnant in them at low tide. But nullipores, barnacles and tube-building worms also live upon the surface, in immense numbers, and construct a very hard and durable substance which, to a certain extent, compensates for the loss of material caused by the sea-urchins. The barnacles and worms build up little walls of limestone around the mouths of the holes and between them, keeping them for a time more or less separated and perfect; but these walls are being constantly broken away, together with much of the surrounding material, resulting in the formation, over most of the outer slope of the surface, of a multitude of irregular, shallow pools, whose edges are protected by the same growth of barnacles and worm tubes. Many projecting masses, also capped with the hard limestone coating, are left standing in the pools, and wearing most rapidly below, they produce mushroom-like structures, which are very characteristic of the outer surface. They reach to the same height as the margins of the pools.

Ordinary sea-weeds grow luxuriantly on the outer edge of the reef, but they are of slight importance compared with the calcareous nullipores, which live in the full face of the surf and form, over large areas, a crust of a foot or more in thickness. Thus the barnacles, worm-tubes and nullipores combined, aid very materially in protecting the reef from wear, but the good they do is more than counterbalanced by the harmful action of the waves and sea-urchins, and, unless the latter are in some way exterminated, they will eventually work much mischief to the harbor of Pernambuco.

The inner slope of the surface of the reef differs from the outer, in not possessing those features which result from the actions of the sea-urchins, and also in being without the nullipore crust. It is generally characterized by a series of shallow basins, lying one below the other along the slope, the rim of each being

protected by barnacles or worm-tubes. These basins are sometimes several feet in diameter and a foot or more deep, and are often very irregular. Prof. Hartt has compared them in appearance to the basins formed by the hot springs of the Yellowstone valley; but while the latter have been formed by deposition, the former result from wear.

Having now finished our rather detailed study of the reef where it is most perfect, we must proceed farther south and see how it terminates. Nearly opposite the mouth of the river described in the first part of this paper, we find a small channel running underneath the sandstone of the reef, and through this there is a constant movement of water. At the sides large blocks have been dislodged, and, tumbling down, have reduced the width of the upper surface to about thirty or thirty-five feet. It thus becomes evident, as has been otherwise proven, that the sandstone reef rests on a very insecure foundation of soft material, which the water has washed out in places, forming covered passage-ways through which there is a strong current, varying in direction according to the time of the tide. Engineers, in boring through the rock, came to loose sand underneath, demonstrating that the structure we are dealing with is only the consolidated capping of a long bar of sand.

To the south of the channel just described, the reef has been much excavated, not only by the waves but by quarrying; this unwarranted destruction of the only object that gives to Pernambuco its prominence as a commercial city has, however, been stopped, and a breakwater has been constructed at this point, but it is now much out of repair. Around the Ilha dos Pinhos the reef curves slightly outwards, and then, bending westward, approaches gradually to the shore, which it skirts for some distance as a narrow line of rocks, almost lying upon the beach. Another small reef begins to the south, and running obliquely, finally joins the beach.

This closes our imperfect description of the reef as it appears at low water; at high tide, on account of the shallow water without, it is played upon by a very heavy surf, which sometimes rolls completely over it, and wave after wave, rising above the outer edge, bursts high into air on striking the artificial wall at the north. During spring tides the water is much agitated within the reef, but not enough to endanger the shipping.

As a result of his careful study of the Pernambuco reef, and of many others of similar character, some of which we will mention farther on, Prof. Hartt has given us the following conclusions regarding the mode of formation of this class of structures :

It is very evident that they are not the out-cropping edges of beds of sandstone, extending out from the shore, as some have supposed, but only narrow strips of stone of slight thickness, formed in exactly the same position in which we see them to-day, that is, just below the level of high tide. They have resulted from the solidification of beach materials, or sea beaches, by carbonate of lime carried into them by the percolating waters. This action goes on from the level of mean high tide to a variable, but only slight, distance below low tide mark, and has only a limited horizontal extension. By the after encroachment of the sea, aided by rivers flowing behind them, these consolidated beaches have often been separated from the main shore as distinct reefs ; but sometimes this latter action has not taken place, and the hardened layer retains its normal position upon the beach.

The agencies concerned in the formation of these hardened beach deposits are mostly very simple ones, many of which can be witnessed by any person visiting the sea-shore. The slope of a sand-beach varies according to the size and character of the sand-grains composing it, the exposure of the coast and the height of the tides. When a wave strikes upon a beach it rushes up the slope in a sheet of foam, carrying with it a quantity of sand. As it returns the sand is spread out over the surface in a thin layer. In this manner a regular lamination, dipping at a more or less even angle, is produced in the material composing the beach. But this regularity is often much disturbed by storms, when the beach may be broken into by the waves and much of its material redeposited at quite different angles.

If the land back of the shore be very low, the beach may form a simple narrow ridge, over which the waves completely break at high water, carrying and depositing sand on the inner side of the beach, where the dip of the laminæ will of course be landward. Ordinarily, however, a ridge of sand is formed behind the sea-beach, above the reach of the tides, being partly due to the action of the surf during storms, but mostly to the winds. Such a beach-ridge as this accompanies most of the Brazilian beaches, which latter, on account of the exposed character of the coast, are formed of quite clean sand, consisting mainly of rounded

siliceous grains, with broken or perfect shells and finer calcareous particles, derived from shells, corals, stony sea-weeds, etc.

The action of the tides is not limited to the surface of the beach, but this, from its porous character, absorbs a certain amount of the water. At low tide the beach just below high tide level is wet but not soaked with water; going downwards, however, we find the beach becoming gradually wetter and wetter until it is completely saturated, producing little rills which run down the surface. With the rise of the tide the level of complete saturation also rises, and when the tide is high the upper part of the beach, for some distance above high tide mark, is completely charged with water, thrown upon it by the waves. A constant movement of water is thus produced in the interior of a beach, but on account of the friction against the grains of sand, this movement can only extend over a comparatively slight width, at least in the upper portions of the beach, which are under the water for only a few hours each day.

Now sea-water, in many parts of the world, and especially within the tropics, is very highly impregnated with bi-carbonate of lime, and this solution, from evaporation or other causes may deposit its lime in the form of a carbonate, which acts as a cement. Where evaporation goes on over a beach wet with sea-water of this character, the surface materials may become consolidated, as occurs at the Abrolhos islands, on the coast of Brazil, and elsewhere. Not only, however, may the upper sands be soldered together, but the hardening may even go on below the level of the sea.

On the Brazilian coast, the surfaces of the beaches are seldom hardened during the ebbing of the tide; but under the hot tropical sun and strong prevailing winds, there must be, in the upper part of the beaches, a concentration of the calcareous solution, which, on sinking downwards to the level of complete saturation, tends to deposit its carbonate of lime as a cement, uniting the grains of sand. The water from rains, percolating through the beaches, may also bring lime, arising from the dissolving of shells and corals in the upper layers, and lagoons, which frequently lie back of the beach ridge, may contribute to the same result. It is evident, however, that the work is mostly done by the sea-water, and that this agent, under certain conditions, has the power of solidifying sea-beaches to a variable distance inland, and to a depth varying from about high tide level to a few feet below low tide level.

If a beach be growing rapidly, or if it is being rapidly worn away, solidification cannot take place, because it is only over a stationary shore, that is neither receiving new accumulations of sand nor parting with its old, that enough time is granted for the accomplishment of this result. Therefore, consolidated beaches must be the exception and not the rule on the Brazilian coast, where the shore is undergoing much change nearly everywhere, and as sandstone reefs seem to be confined to that single country, it must be that there alone are the proper conditions attained for their formation. The hardening appears to extend from the outer side of the beach inwards, and from below upwards, as new reefs usually lie on the lower and outer part of the beach; the younger reefs are also softer in texture than the older, more-finished ones.

It is probable that many of the ordinary Brazilian beaches are solidified below the surface, but until something happens to uncover them, it is impossible to determine the fact. Reefs in process of formation are to be seen on the coasts of both Pernambuco and Bahia, and at Porto Seguro; in the latter province, there is a double reef, the outer one being the wreck of an unfinished structure, the inner still undergoing solidification.

Prof. Hartt was led to believe, from his earlier studies of the Brazilian stone reefs, that a slight elevation of the land was necessary to account for their present position; but his later studies proved to him that such an hypothesis was wholly uncalled for, and that none of the reefs reach above high tide level, or at the most above the level to which a beach is saturated with water at high tide.

Statements have been published that a certain amount of upheaval must have occurred to produce the supposed strong seaward dip of the laminæ of the sandstone; but nowhere, excepting on edges where blocks have been undermined and tilted up, is the inclination greater than might obtain on a sand-beach. To suppose an upheaval to have effected these narrow lines of reef, tilting the strata evenly in one direction, and no part of the neighboring coast, is a geological absurdity. The reefs follow the general trend of the shore, and are more or less curved, but generally straighter than the beaches immediately back of them.

Having shown that the curious reef at Pernambuco, which for many years was a complete puzzle to explorers, has been formed through the agency of very simple forces, in part working upon

every sand-beach in the world, we will hastily glance at the other evidences of the same phenomena on the Brazilian coast.

The northern-most consolidated beach examined by the Geological Commission, is near the mouth of the Rio Parahyba do Norte, where, to the south of a fringing coral reef, there are traces of a short and imperfect stone reef lying upon the shore. Stone reefs have, however, been recorded from north of this point by other observers, but they have never been described; one is situated at the mouth of a small river, about eighteen miles north of the Parahyba do Norte, and another lies in front of the Rio Potengy, in the province of Rio Grande do Norte.

Directly to the south of Cape Sto. Agostinho, in Pernambuco, is the most perfect stone reef discovered; it is almost absolutely straight, its northern end being separated from the cape by only a narrow break or bar, encumbered by loose blocks of reef rock. The land back of the reef, being very low, has been swept deeply away, forming a broad and very shallow bay. The inner edge of the reef is honeycombed and as irregular as that of a coral reef, while the shallow basins of the median and inner portions of the surface are much developed, forming regularly terraced plateaux.

At Rio Formoso, in the same province, there is another stone reef, reaching only about three feet above mean low tide, and not having a great length. The joints dividing the reef-rock are often filled in with sand, which has sometimes been solidified. On the island of Santo Aleixo, not far distant from Rio Formoso, is a small reef of soft texture, lying alongside the beach, and other imperfect reefs also occur in this vicinity on the main shore.

Nowhere near the city of Bahia do we find perfect sandstone reefs; but at the mouth of the bay of Bahia, close to the lighthouse on the outer shore, and on some of the inner shores of the bay, layers of consolidated material occur, capping the beaches and at times covering quite extended areas. They are often composed of very coarse materials and contain many shells, and illustrate beautifully, in many cases, the irregularities of beach bedding.

On the western side of the same bay, at Porto Santo, there is a curious example of consolidated beach structure, the only instance of the elevation of such material of which we are aware. At this place we find a cliff back of the beach, having a length of about 1,100 feet, and a greatest height of about thirteen feet, and composed almost entirely of sand and gravel, cemented by lime into a sandstone. The lower part of the cliff is very hard

in texture, and contains numerous fragments of corals and shells, the latter being frequently found entire. Many of the species of both exist in abundance throughout the bay. The upper part of the cliff is of almost pure sand, and has been so incompletely hardened as to crumble readily between the fingers. The amount of calcareous material in the lower portion is very great, and it is said to yield a good quality of lime on burning.

Whether this cliff belongs to the same class of structures as the reefs or not, it is, at least, composed of the same materials, and must have been formed in about the same way. Its present elevated position—for high water reaches only slightly above its base—indicates that the shore has been raised at this point to a height nearly equaling that of the cliff. What gives an increased interest to this locality is the presence of a low kitchen-midden, only two or three feet thick, which overlies the entire cliff. It is composed of a dark-colored, sandy earth, packed full of the shells of the edible mollusks of the bay, with a few scattered bones, and occasionally a human skeleton.

The stone reefs of the southern part of the province of Bahia, have been very fully described by Prof. Hartt, in the "Geology and Physical Geography of Brazil." The principal ones are those of Porto Seguro and Santa Cruz, both being similarly situated and of about the same character. The former is the larger, and, beginning in front of a small bay formed at the mouth of a river, runs southward, skirting the shore for a long distance. In general structure it is like the Pernambuco reef; the outer edge has become very jagged, from the undermining and falling down of blocks. But below the level of low water, the reef-rock extends seaward a hundred feet or more, forming a very shallow tract, over which one may wade when the tide is out. The inner edge is much thinner than the outer, being often overhanging, and it is flanked by a sloping bank of mud. The surface is of very uniform height, but quite rough, and interrupted by cracks and pools, which teem with marine life. From fractures at the end, it is apparent that the hardening has taken place to a depth of several feet below low tide.

At Gaurapary and Barra Secca, in Espirito Santo, and in their vicinity, are several imperfect reef formations, similar to many already described; and at the Abrolhos islands, as before stated, the sand and shingle beaches are often firmly consolidated by a lime cement.